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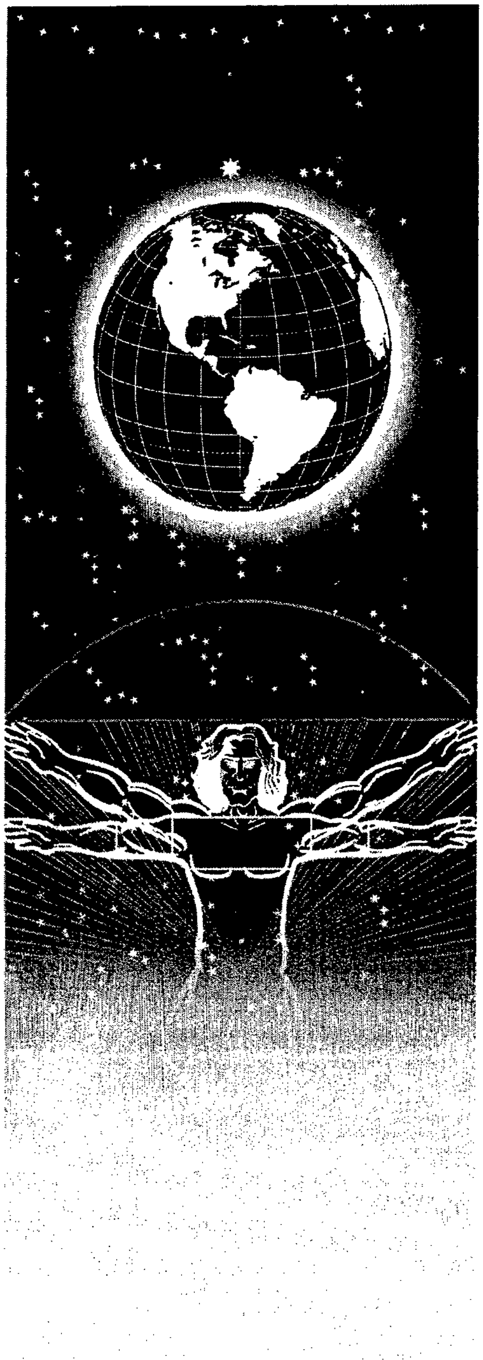

UNITED STATES AIR FORCE RESEARCH LABORATORY

A DUAL HAPTIC INTERFACE INVESTIGATION FOR IMPROVED HUMAN-COMPUTER INTERACTION

D. W. Repperger

HUMAN EFFECTIVENESS DIRECTORATE
CREW SYSTEM INTERFACE DIVISION
WRIGHT-PATTERSON AFB OH 45433-7022

Ling Rothrock

DEPARTMENT OF BIOMEDICAL, INDUSTRIAL AND HUMAN FACTORS ENGINEERING
WRIGHT STATE UNIVERSITY
3640 COLONEL GLENN HIGHWAY
DAYTON OH 45435-0001

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Human Effectiveness Directorate
Crew System Interface Division
2255 H Street
Wright-Patterson AFB OH 45433-7022

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FOR THE COMMANDER

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D.W. Repperger
L. Rothrock*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

* Department of Biomedical, Industrial, and Human Factors Engineering
Wright State University
3640 Colonel Glenn Highway
Dayton OH 45435-0001

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13. ABSTRACT *(Maximum 200 words)*

This study involved designing haptic interfaces with the assistance of genetic algorithms. Five subjects were initially run in a pilot study and from these preliminary data, a model was developed to predict the response of all subjects to 65,536 possible experimental conditions. A multiobjective performance function was developed and the genetic algorithm methodology was utilized to search for the optimum experimental design conditions through a MATLAB/SIMULINK simulation. In a post hoc study, seven subjects were then evaluated with the optimum condition as well as alternative conditions over the range of the possible independent variables of interest. The subjects demonstrated that both their performance and situational awareness measures were significantly improved at the optimum design condition in the post hoc study as compared to the pilot study. The overall effort emphasized the concept of experimental design parsimony. What this means is that a few experimental conditions are initially run with a few subjects and that a computer model then generalizes the pilot data to predict the results in a more general setting. The post-hoc study then validates the initial assumptions and modeling incorporated in this effort.

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A Dual Haptic Interface Investigation for Improved Human-Computer Interaction[1]

D. W. Repperger[2] Ling Rothrock[3]

[2] Air Force Research Laboratory, AFRL/HECP, WPAFB, Ohio, 45433-7022, USA, e-mail:D.Repperger@ieee.org (corresponding author)

[3] Department of Biomedical, Human Factors and Industrial Engineering, Wright State University, Dayton, Ohio, 45435, USA, e-mail: lrothroc@cs.wright.edu.

For virtual reality systems and in the design of synthetic environments, sophisticated interface devices need to be employed with operators to enhance their immersive experience. A dual haptic condition was explored in this study to investigate better means of improving how humans may interact with computers or other complex systems. Two types of haptic feedback were utilized in an independent manner. A force reflecting joystick employed cutaneous (skin sense) cues to the operator as one experimental variable of interest. A second type of haptic interaction involved motion chair proprioceptive cues (forces felt inside the body at tissues, tendons, and bones). Seven subjects were utilized involving these two factors with 256 levels of force reflection possible within each factor. Data analysis of two dependent performance measures related to speed and accuracy during tracking was performed. In a post hoc study, it was seen that certain optimum levels of the two haptic independent variables improved the human-computer interaction as measured by the dependent performance variables of interest studied here.

KEYWORDS: haptic interfaces; controls; optimized human-computer interaction.

1. INTRODUCTION

Synthetic environments involving virtual reality are of much recent interest in how they may be manipulated to improve the human-computer interaction (Wann & Mon-Williams, 1996, Wilson, 1997, Stone, 2001, and Stedmon & Stone, 2001). The sense of presence in these artificial environments is a key attribute of interest, which is desired to be enhanced (Loomis, 1992, Tromp, 1995, Nichols, Haldane & Wilson, 2000). One can see, for example, the importance of this

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characteristic within the context of telecommuting (Bredin, 1996, Apgar, 1998, Venkatesh & Speier, 2000), and with the use of alternative controls (Ledermann & Klatzky, 1987, and Burnett & Porter, 2001) to provide means of improving the presence of the operator about a remote environment. It is sometimes viewed that "All behavior is the control of perception" (Powers, 1973 and Farrell, Hollands, Taylor, & Gamble, 1999) with manipulation of perception as a gateway to modifying behavior, hopefully in a productive manner.

One possible means of improving the interface between the operator and his computer or machine is through the use of a haptic manipulandum (Brooks, Ouh-Young, Batter, & Kilpatrick, 1990). The term "haptics" broadly refers to both sensing and control manipulation using a *tactual* sensory system (Clark & Horch, 1986 and Tan & Pentland, 2001). It is generally viewed that this tactual sensory system has two subsystems: the tactile (or cutaneous) sense and also the kinesthetic sense (proprioceptive). The cutaneous sense refers to stimulation on the body surfaces via mechanoreceptors close to skin surfaces. This signal could be mainly an afferent response to an external stimulus. The second haptic sense (kinesthetic) includes proprioception, which involves the awareness of the limb positions, movements, and muscle tensions derived from the muscles, skin, and joints including knowledge of motor commands sent to the muscles (efferent signal). Thus, both afferent and efferent signals may contribute to a haptic perception and a haptic controller may be viewed as both a display and a controller.

In the design of car interfaces, touch screens and other interactive devices have found success (Burnett & Porter, 2001), as well as for computer mouse control (Akamatsu & Mackensie, 1996), for landing control of aircraft in virtual environments (Repperger, Haas, Brickman, Hettinger, Lu, & Roe, 1997) and for rehabilitation studies (Repperger, Phillips & Chelette, 1995). An example of the cutaneous haptic interaction occurs with touch pads which can provide an important force feedback (Jensen, Radwin, & Webster, 1991 and Tang, Neebe, & Kramer, 2001). Models also exist for the proprioceptive aspects of this interaction (McMahon, 1984 and Powers, 1999). Haptics will increase in importance with Web-based applications. There are numerous studies that indicate success in this medium is predicated on how you move through complex information, for example, how navigation is performed in Web searches (Carmel, Crawford & Chen, 1992, Vicente, Christoffersen & Pereklita, 1995, Burns, 2000 and Spence, 1999).

In this paper, a class of possible cutaneous (joystick) and proprioceptive (motion chair) haptic variables were investigated that may influence key performance attributes of the human-machine interaction. A multi-objective performance function was utilized involving fundamental

performance attributes related to tracking over a wide range of possible experimental conditions (256 levels of each factor). Speed accuracy measures linked to tracking performance are important dependent measures used in the experimental paradigm to be described next.

2. METHOD

2.1 SUBJECTS

A total of seven subjects participated in this experiment. A subject panel from a local contractor at the Wright-Patterson Air Force Base in Ohio, USA provided five (two males and three females) of the participants. Two additional male subjects were government employees. These adult people (ages ranged from 19 years to 52 years) were either housewives or students at a local university being employed part time. The compensation for participation in this experiment was $6 dollars (US) an hour of their participation for the contracted personnel.

2.2 APPARATUS

A force-reflecting joystick supplied haptic cues at the subject's hand and a motion chair device provided proprioceptive cues as a second factor. This single-axis motion platform was outfitted with a dual axis force reflecting joystick controller (Immersion 2000) as displayed in Figures 1 and 2. This device was constructed from a welded aluminum frame rigidly

Figure 1. Motion Base Simulator used in Pilot Study

Figure 2. Proximal Distance from the Base to the Tracking Display

supporting a racing car seat. Padded armrests are configured at an elbow level, while the joystick is mounted such that its handle may be comfortably grasped by a seated pilot's right hand. Joystick motion was restricted to the lateral axis, the axis parallel to the motion of the chair. The entire

frame translates sideways on a Ball Screw assembly with an 18-inch stroke. Translation is driven by a Kollmorgen Model B-404-B DC Servo Motor, which is rated at 4.5 hp.

The Immersion IE (Impulse Engine)-2000 powered joystick is a two-degree of freedom force-reflecting manipulandum used in haptic experiments. It generates 4.04 Newtons maximum force at the handle grip to the human operator, which is displaced 0.1397 meters from a pivot point. This device measures position displacement of the stick through digital encoders and applies a force feedback interface via a cable drive. The force reflection algorithms are programmable in C+ code. The forces generated by this haptic device are independent of the chair's motion but the chair may induce a physical interaction upon the human operator to generate biodynamic feedthrough at the joystick.

2.3 PROCEDURE

Objective: It is desired to demonstrate that there exists an optimum design of the two haptic inputs (optimum levels of forces created by the joystick and chair motion) which will improve certain measures of human performance in a post hoc evaluation with human subjects. This can also be restated as a null hypothesis:

Hypothesis

The null hypothesis it is that there is no difference in human performance by manipulating certain haptic parameters involving the joystick and motion chair device. Thus:

Ho: There is no difference in certain performance dependent measures due to particular haptic design parameters of the joystick and motion chair, versus the alternative hypothesis.

H_1: At least one performance measure may be significantly affected by a level of a certain haptic condition.

2.4 THE PERFORMANCE TASK

In figure 3, the subject had to minimize the time the cross is outside the box. The subject controls the cross, which is acted upon by the target input forcing function (f_t). Figure 4 illustrates a control loop diagram in which the two forcing functions f_t (target input) and f_d (disturbance input) enter the system. f_d affects chair motion, only.

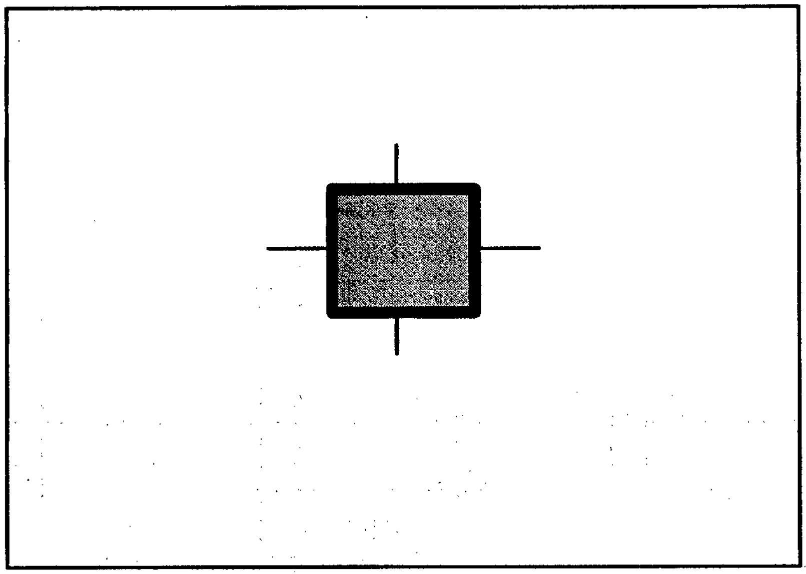

Figure 3. User Tracking Task Subject to Target (visual) and Disturbance (haptic) Forcing Functions

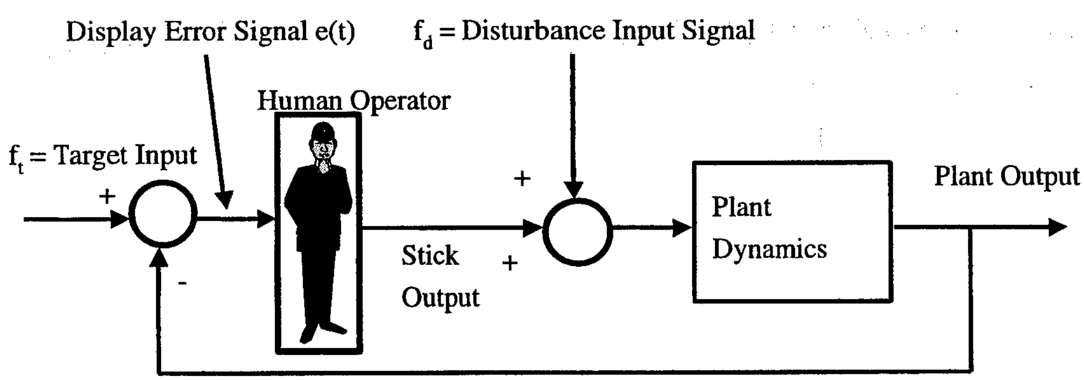

Figure 4. The Human-Machine Problem of Interest

In figure 4, the human appears in a loop observing a display containing a target forcing function f_t. A second forcing function f_d is a disturbance input. The goal of the operator in the loop is disturbance rejection of both the target (f_t) and the disturbance (f_d) forcing functions. This means that one goal is to minimize the tracking error e(t) in the loop as displayed in Figure 4. Operationally this is equivalent to maintaining a constant pose (constant attitude and orientation), e.g. when a helicopter is in a search and rescue mission at a low altitude and subjected to wind turbulence. The operator, in this case, must keep the position and orientation of the airship constant, despite the induced wind turbulence. For this study, levels of the haptic independent variables are related to the spectral characteristics of f_t and f_d. Both the target and disturbance input forcing functions are constructed to be the sum of a selected group of sine waves.

The deterministic input-tracking tasks $f_t(t)$ and $f_d(t)$ were composed of the sum of 8 distinct sine waves (prime number multiples of a fundamental harmonic) of sufficiently high frequency content that they appeared quasi-random to the human operator. A means of developing such tracking tasks is discussed, for example, in the appendix of (Repperger, Rogers & Bianco, 1983). It is well known that when 5 or more sine waves are randomly added, it becomes exceedingly difficult for the operator to predict the next movement of the target; hence it has the appearance of a random tracking task, although derived from a deterministic signal.

2.5 CONSTRUCTION OF THE LEVELS OF THE TWO HAPTIC FACTORS

With respect to the prior discussion, the two key parameters f_t and f_d become the factors that are to be investigated here. First a description on how the 256 levels of each factor were constructed is given. The dependent, performance related parameters, which become key elements of the objective function to be minimized are then presented.

2.5A Construction of the 256 Levels of Each Haptic Factor:

To find the class of possible target and disturbance forcing functions, Figure 5 displays an eight-bit word to describe how the different haptic levels will be defined. Each forcing function (f_t or f_d) is represented by the following series (i = t or d for target and disturbance, respectively):

$$f_i = \sum_{j=1}^{8} a_j \sin(\omega_j t + \phi_j) \qquad (i = \text{t or d}) \tag{1}$$

where the eight coefficients a_j can be either high (1) or low (0) to be consistent with Figure 5. The high and low representations are described by a one or zero as viewed within the context of an 8 bit word commonly used in computer programming (figure 5). Since $2^8 = 256$, this presents a paradigm to have this many levels of haptic force reflection. In actuality, with equation (1) for f_i, the low value of the coefficient a_j was selected as 1.0 and the high value of a_j was selected as 2.0. Thus each forcing function was the sum of 8 sinusoids with the nonzero coefficients as either 1 or 2. The bandwidth of the forcing function f_i in equation (1) was limited to 2 Hz, since human tracking rarely is successful for frequencies beyond that range. This forcing function is actually a deterministic signal but appears quasi random to the human. For more discussion on this topic, please refer to the appendix of

$2^8 = 256$ Possibilities

1 or 0	**1 or 0**	**1 or 0**	**1 or 0**	**1 or 0**	**1 or 0**	**1 or 0**	**1 or 0**

Figure 5. The Class of Forcing Functions as An Eight Bit Word

Repperger, Rogers & Bianco, 1983. Figure 6 displays a spectral analysis of the forcing function designed for the word "10000000". In the construction of the forcing function, three additional steps need to be taken. First, the fundamental frequency ω_o is the reciprocal of the total time of a run length (i.e., 98 seconds). Second, the selected frequencies ω_j in equation (1) are prime number multiples of

ω_o. This keeps the Fourier analysis from having a foldover effect if any two ω_j and ω_k were precise integer combinations of each other and $j \neq k$. Third, the target and the disturbance forcing functions are assigned different prime number multiples of ω_o so they could be analyzed separately to reduce any possible cross correlation that may exist between these variables.

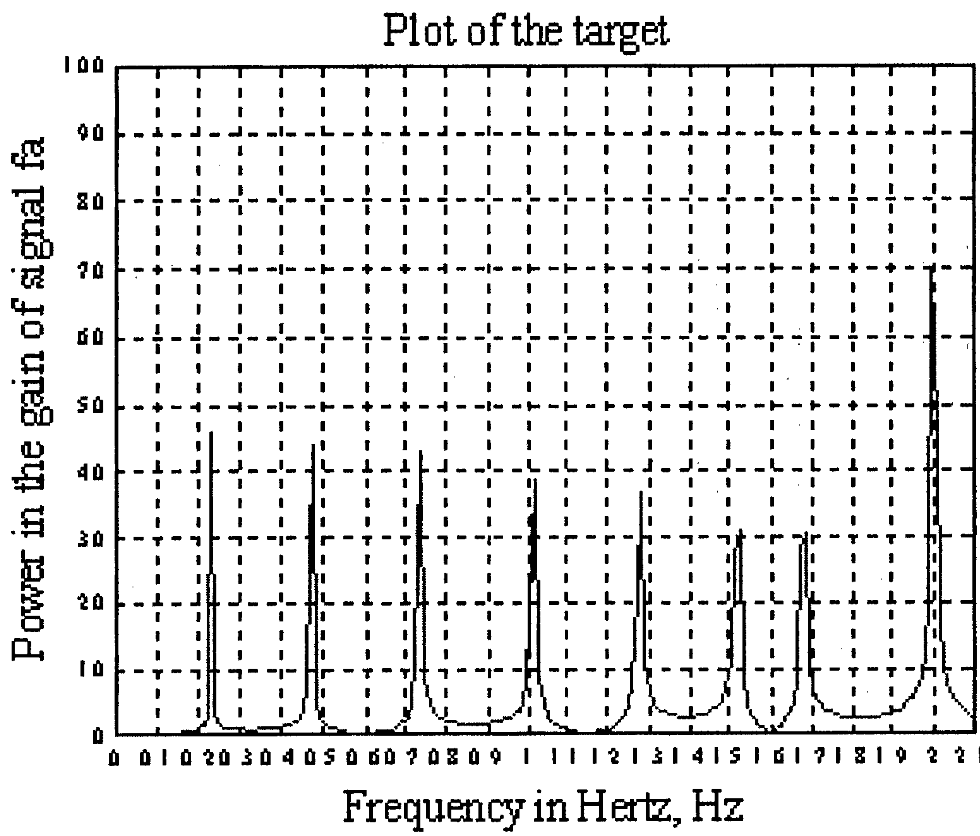

Figure 6. Plot of the target forcing function.

2.6 CONSTRUCTION OF THE KEY DEPENDENT MEASURES OF PERFORMANCE

It is desired to obtain a multiobjective performance metric to capture both speed and accuracy aspects of human tracking. To achieve this goal, certain key dependent measures will be considered. First, for accuracy, the variable T(e) is defined as:

(1) Time out of the box T(e(t)).

The time out of the box is determined by the integrated time the error signal gets bigger than a threshold Δ and can be expressed:

$$T(e(t)) = \int_0^t dt' \quad \text{if } |e(t)| > \Delta \text{ for } t \,\varepsilon\, [0, t_f] \tag{2}$$

where t_f is the time duration of the tracking task = 98 seconds. Thus if the T(e(t)) variable is 9.8 seconds, this implies the error signal gets bigger than the box size Δ for about 10% of the time during the tracking task. This is truly an accuracy measure in the sense that large deviations need to be penalized.

The second dependent measure is related to the speed in capturing a target.

(2) Gain of the human machine systems defined in the figure 7:

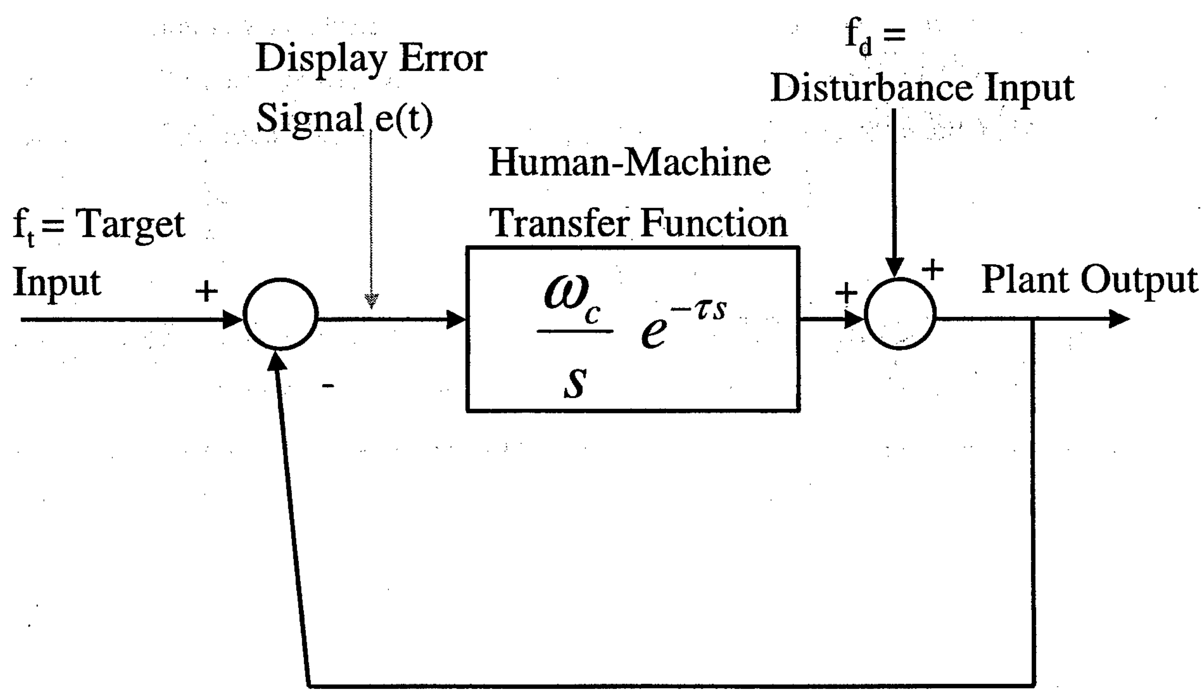

Figure 7 - The Crossover Model of Human-Machine Interaction

Figure 7 represents a classical model of human-machine interaction termed the "Crossover Model", McRuer, Graham & Krendel (1967), which has been widely accepted in the literature to describe human-machine interaction. The simplicity and parsimonious nature of the model have made it an attractive means of describing human behavior in a manner that is easily understood. Also, such a model is "invariant" in the sense that it can generalize when certain system parameters

change. The parameter ω_c is the crossover frequency and represents an approximate measure of the bandwidth of the closed loop system between f_t and the plant output variable. The *s* variable is the Laplace transform and the presumption is that the time delay τ is relatively small for this study. The plant dynamics are unity in this analysis so that the variable f_d can be assumed to appear at the plant's output.

The gain of the open loop in Figure 7 (g_1 or g_2) is closely related to the term ω_c which can be empirically determined in the data by taking the transfer function between the plant's output and the error signal input and evaluating an approximation of this overall gain. This can be shown to be related to speed-accuracy tradeoffs since g_1 is a quantity determining how fast a target is acquired (bandwidth measure). The multiobjective performance function to be minimized is thus specified via:

$$J_1(f_t, f_d) = (T(e))^2 + (k_1/g_1)^2 + (k_2/g_2)^2 \tag{3}$$

Since the variables T(e) and g_1 or g_2 trade off (accuracy versus speed), then the reciprocal of g_1 or g_2 is used in equation (3) since it is desired to minimize J_1. The constants k_1 and k_2 of equation (3) are employed to normalize the three variables since they have different units. The optimization problem can be stated as the determination of the best selection of f_t and f_d to minimize J_1, i.e. find:

$$\min_{f_t\ f_d} J_1 = (T(e))^2 + (k_1/g_1)^2 + (k_2/g_2)^2 \tag{4}$$

subject to the transfer function representation in Figure 7.

2.7 TRAINING

In the pilot study, on the first day, subjects tracked 5 runs of 2 minutes duration with no chair motion or stick feedback (baseline condition). The second and subsequent days they received the sixteen experimental conditions depicted in Figure 8 (pilot study) after running the baseline condition, initially.

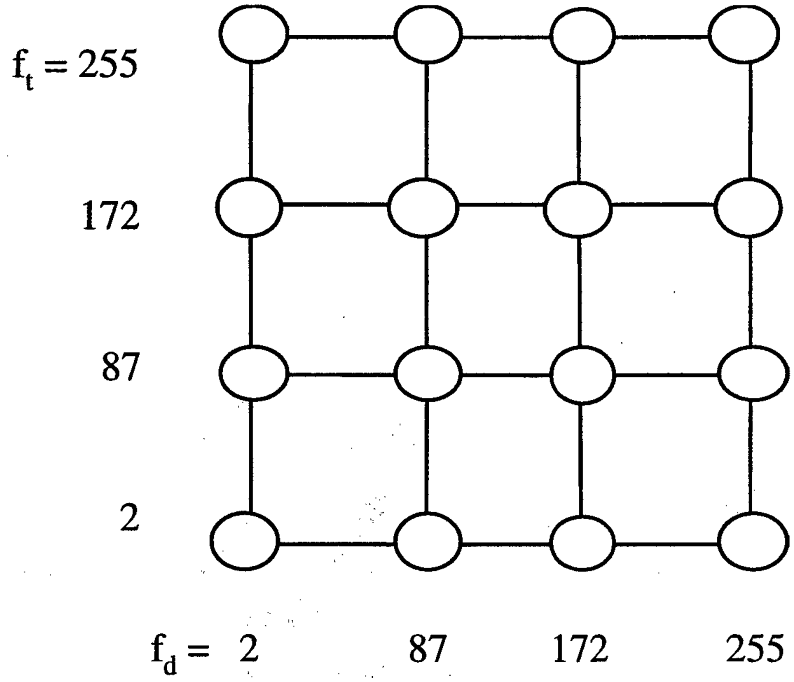

Figure 8. Pairs of Target and Disturbance Forcing Functions Used in Pilot Study

2.8 EXPERIMENT DESIGN

In this investigation, a wide range of possible levels of the two haptic variables of interest were selected to be examined so as to span the possible experimental design space. This was accomplished with a six step process:

(1) Take pilot data from a small number of experimental conditions which span the extremes and other way points of the possible design paradigm (cf. figure 8).

(2) Dependent measures related to speed and accuracy were extracted (T(e) and g_1 and g_2 of equation (3) experimentally obtained from the pilot study). Empirical models were then developed on how g_1 and g_2 changed with levels of the two haptic factors.

(3) A mathematical model was then constructed to simulate the human-computer interaction over all levels of the two factors. T(e) was also calculated in the computer simulation.

(4) The multiobjective function (involving the key dependent measures from step 2) was calculated via computer for all 256x256= 65,536 possible design conditions.

(5) Using an optimization procedure (random directed search or Genetic Algorithm), an optimal set of parameters (levels of each haptic factor) of the multiobjective function was determined via the computer simulation (Rothrock & Repperger, 2002).

(6) A post hoc experiment was then conducted with human subjects. The optimum predicted design was tested to verify if the design of interface parameters shows the desired optimality in terms of the multiobjective function selected in step 4 (given in equation (3)).

2.9 DATA COLLECTION

Fifteen channels of data were collected. The most relevant variables include the stick displacement output, chair motion, stick force, target motion as well as the time derivatives of a number of these variables. The analysis reported here includes performance (time out of the box = T(e) and the gain terms g_1 and g_2) from the operator.

3. RESULTS

3.1 RESULTS FROM THE PILOT STUDY AND COMPUTER SIMULATION

The first experimental results are a consequent of the pilot study portrayed in figure 8. The empirical rules regarding the gain terms g_1 and g_2 had to be evaluated for different levels of the forcing functions f_t and f_d. To illustrate the complexity of such relationships, we list here the empirical rule expression for g_1 as determined from the pilot study data as an example of how

$$g_1(f_t, f_d) = 112.5 + (0/155)*t + (40/98)*d \qquad \text{for} \qquad (t\ \varepsilon\ [1,128],\ d\ \varepsilon\ [1,128]) \quad (5a)$$

$$g_1(f_t, f_d) = 203 - (33.5/155)*t - (40/98)*d \qquad \text{for} \qquad (t\ \varepsilon\ [129,256],\ d\ \varepsilon\ [129,256]) \quad (5b)$$

the gain parameter g_1 would vary dependent on the level of the target forcing function f_t as well as the disturbance forcing function f_d.

As a result of steps 3 and 4, the output of the computer simulation describing the multiobjective function J_1 as described in equation (3) over the entire range of levels for both haptic variables was calculated. Figure 9 displays the complex nature of this multiobjective function.

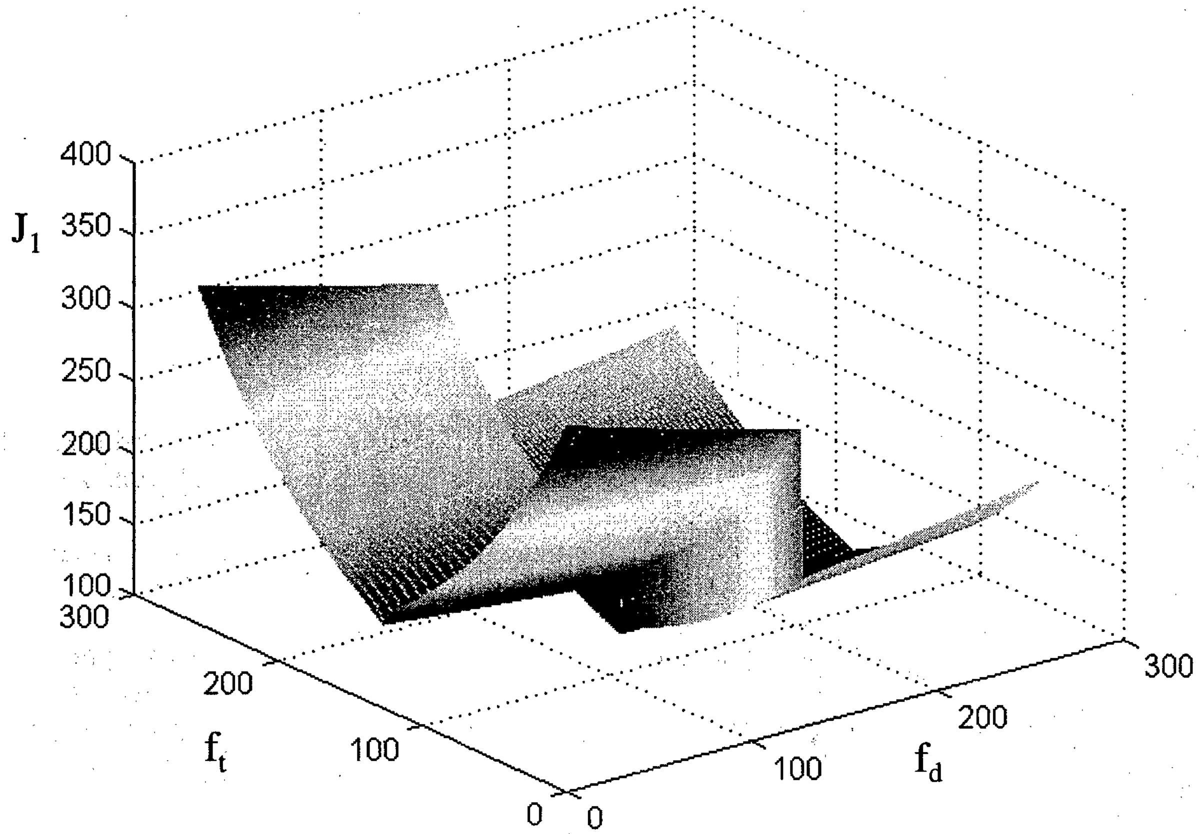

Figure 9 – Plot of Multiobjective Function over all levels of Haptics

The next set of results concerns the post hoc validation study.

3.2 RESULTS OF THE POST HOC STUDY

As described earlier, the multiobjective function of figure 9 was searched for a global minimum and those levels of haptic variables were selected as the optimum operating point. A post hoc study then evaluated the optimum point versus alternative designs. In figure 10, an illustration is given for the experimental design involving the post hoc validation process.

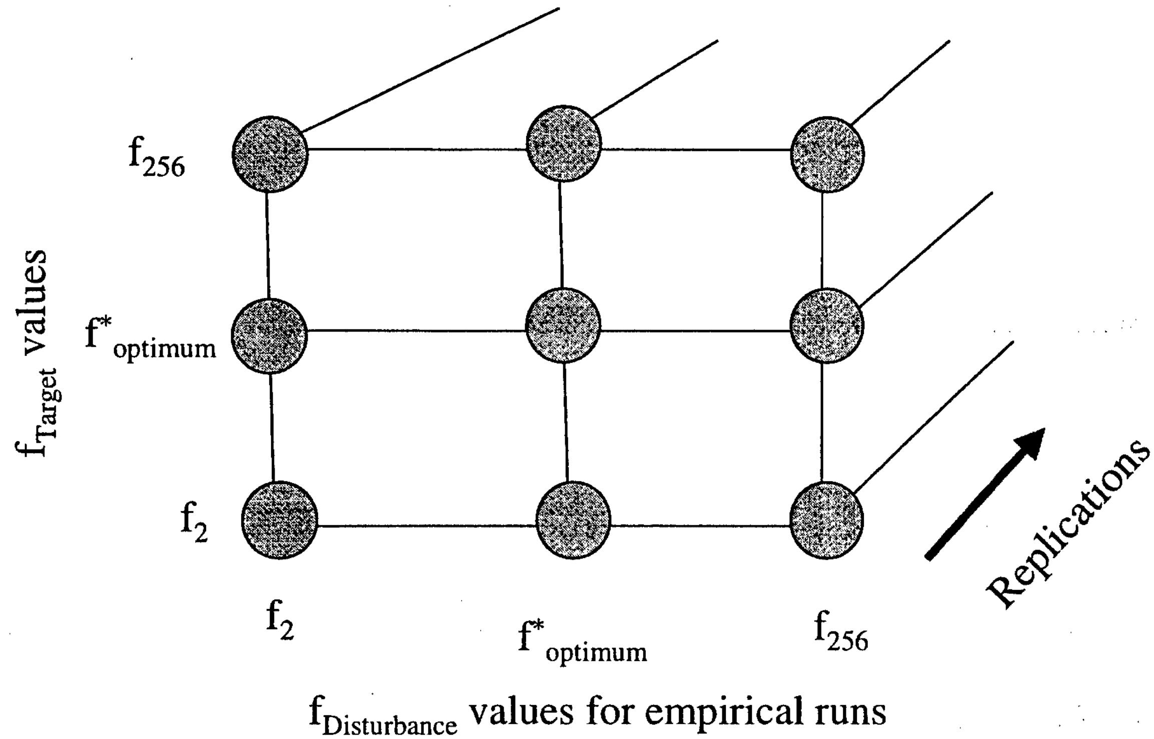

Figure 10 – Post Hoc Experimental Design Matrix for Validation

4. POST HOC EXPERIMENTAL VALIDATION

As illustrated in figure 10, five of the original seven subjects ran a post hoc experimental study with the optimum design conditions and two alternative levels of each haptic variable. This was a repeated measure design where each subject was run at every condition depicted in figure 10. The J_1 variable was calculated and the results are displayed in Table I.

Table I - Results of Post Hoc Study for J_1 Values (averaged across 5 subjects)

	Disturbance f_{d-2}	Disturbance f_{d-2}	Disturbance $f_{d-optimum}$	Disturbance $f_{d-optimum}$	Disturbance f_{d-256}	Disturbance f_{d-256}
Target f	$J_{1\text{ - mean}}$	J_1 - S.D.	$J_{1\text{ - mean}}$	J_1 - S.D.	$J_{1\text{ - mean}}$	J_1 - S.D.
f_{t-256}	278.86	24.23	200.95	14.57	212.21	35.73
$f_{t-optimum}$	162.95	55.56	132.15	41.86	138.99	42.94
f_{t-2}	298.29	34.74	174.43	61.09	186.97	93.55

Since this was a within subjects (repeated measures) design, blocking across subjects occurred with reduced this source of variation (within a block, however, all other experimental

conditions were randomized). We look at the main effects and study their respective interactions. These data were analyzed using JMP 4.0, the latest statistical package from the SAS Institute. It is emphasized that the subjects were the random effects variable in this analysis. Also in this full factorial design (for the factors in figure 10), all treatments were presented randomly and the subjects had no indication which level of f_t or f_d was administrated during the post hoc analysis runs.

From the data in Table I, an ANOVA was then conducted with J_1 evaluated from the dependent measures collected from the five subjects. The results are displayed in Table II.

Table II - Results from the AVOVA from the Post Hoc Study ($p < .05^*$)

Source	Sum-Squares	Mean Squares	Degrees of Freedom	F Ratio	Prob > F
f-target	65,813.6	32,906.8	2	51.4330	< .0001*
f-disturbance	53,221.5	26,610.8	2	6.2882	.0228*
$f_t * f_d$	13,607.6	3,401.9	4	1.1851	0.3548
f_t * subject	5,118.39	639.799	8	0.2229	0.9813
f_d * subject	33,854.9	4,231.87	8	1.4742	0.2418
f_t*f_d*subject	45,930.6	2,870.66	16	2.3453	0.2126

5. DISCUSSION:

From Tables I and II, it is clear that J_1 achieved a minimum at the optimum points in contrast to the extreme points in which it was evaluated during this post hoc analysis. Table II indicated no interaction between the two main effects f_t and f_d and the possible interactions with subjects was also not significant. The subjects were the random effect in this analysis. The influence of f_t on J_1 seems more pronounced than the effect of f_d. This is consistent with prior work in which this type of task, related to accuracy, can be easily degraded when the target forcing function is made quickly moving, making disturbance rejection more difficult. f_d has less effect on the objective measure J_1 which is consistent with findings in haptic studies when proprioceptive feedback produces less degradation on this type of tracking performance.

6. CONCLUSIONS:

It has been demonstrated that certain mixtures of two possible haptic variables may be productive in reducing key attributes of human performance in a dual haptic study. Both cuteneous and priopriоceptive haptic variables were considered. A multiobjective performance criteria was utilized to glean out measures of both speed and accuracy, which are important variables related to tracking.

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